BIOELECTRIC IMPEDANCE DETECTS FLUID RETENTION IN PATIENTS UNDERGOING CARDIOPULMONARY BYPASS

Excessive fluid accumulation is associated with increased morbidity and prolonged convalescence after cardiopulmonary bypass. However, water fluctuations are difficult to assess solely on the basis of changes in body weight and fluid balance. Bioelectric impedance analysis is a simple, rapid, noninvasive bedside technique that measures the resistance of the body to a weak alternating current (50 kHz). The change in resistance is inversely proportional to the change in total body water. To investigate the relationship between body weight, fluid balance, and resistance, 18 patients who had cardiopulmonary bypass (9 men, 9 women, aged 61 ± 3 years, weighing 80 ± 4 kg, with ejection fraction 54% ± 3% and bypass time 113 ± 8 minutes [mean plus or minus standard error of the mean]) were followed up for 7 postoperative days. Body weight, fluid balance, and whole body and regional resistance were determined at 24-hour intervals. In the immediate postoperative period, fluid retention was accurately detected by simultaneous measurements of weight gain and decreased resistance ($p < 0.001$). Both measurements detected the initiation of diuresis by postoperative day 2 ($p < 0.01$). Whole body resistance returned to baseline values by day 7 ($p > 0.05$), and body weight returned to baseline on day 4 ($p > 0.05$). Change in weight and change in whole body resistance were highly correlated with cumulative fluid balance ($r = 0.84$, $p < 0.001$, and $r = -0.81$, $p < 0.001$, respectively), and these two measures were also related to each other throughout the study ($r = -0.89$, $p < 0.001$). The initial change in resistance was the best measurement associated with postoperative outcome ($p \leq 0.01$). The data suggest that the measurement of electric resistance across the body can accurately detect acute changes in total body water and in fluid redistribution through the body. However, determining the relative day-to-day change in whole body resistance seems more appropriate than calculating absolute fluid changes over time. Bioelectric impedance offers a simple, rapid, noninvasive method to monitor serial changes in total body water. This technique can be useful in situations in which rapid alterations in water compartments occur, and it may be useful in predicting outcome after cardiopulmonary bypass. (J THORAC CARDIOVASC SURG 1995;110:111-8)

Jorge Gonzalez, MD, Thomas Morrissey, MD, Theresa Byrne, MS, RD, Robert Rizzo, MD, and Douglas Wilmore, MD, FACS, *Boston, Mass.*

From the Laboratories for Surgical Metabolism and Nutrition and the Division of Cardiac Surgery, Department of Surgery, Harvard Medical School and the Brigham and Women's Hospital, Boston, Mass.

Supported by National Institutes of Health Trauma Center Grant No. 5P50-36428.

Received for publication May 30, 1994.

Accepted for publication Dec. 8, 1994.

Address for reprints: Douglas W. Wilmore, MD, Brigham and Women's Hospital, Surgical Metabolism and Nutrition, Thorn Research Building, 14th Floor, 20 Shattuck St., Boston, MA 02115.

0022-5223/95 $3.00 + 0 **12/1/62949**

Water metabolism is markedly disturbed in patients undergoing heart operations who require cardiopulmonary bypass (CPB).[1] During the course of the operation impaired tissue perfusion, regional hypoxia, complement activation, and the release of vasoactive substances (such as lysosomal enzymes, endotoxins, and kinins) increase capillary permeability.[2-4] The leakage of plasma proteins from the vascular compartment and the loss of proteins on the CPB circuit further decrease plasma oncotic pressure and contribute to extravascular water accumulation.[5-7] In addition to preexisting disease, factors that alter normal water distribution include

Table I. *Preoperative characteristics of patient population*

Patient	*Sex*	*Age (yr)*	*Weight (kg)*	*% IBW*	*Height (cm)*	*Diagnosis*	*CHF*	*Other*	*Albumin (gm/dl)*	*LVEF (%)*	*TBW (L)*
1	M	47	88.6	114	186	CAD	–	HTN	4.8	65	47.8
2	F	84	67.3	114	160	CAD	–	HTN, MI, DM	3.1	64	31.7
3	F	48	74.8	124	158	CAD	–	HTN, MI, DM	3.4	63	33.6
4	F	65	67.2	118	154	CAD	+	HTN, DM	4.4	53	32.3
5	M	42	84.0	115	165	CAD	–	HTN, MI	4.4	45	42.6
6	M	48	73.6	110	168	CAD	–	HTN, MI, DM	4.5	42	45.7
7	M	69	122.0	134	184	MVD	–	HTN	4.6	73	54.9
8	F	79	70.0	121	155	CAD+AVD	+	HTN	3.8	60	34.3
9	M	70	102.8	122	184	CAD	–	HTN, DM	4.1	70	55.2
10	F	78	61.0	105	150	CAD+AVD	+	HTN, COPD	3.0	50	35.5
11	M	60	87.9	108	180	CAD	+	HTN, MI	3.4	35	49.3
12	F	76	62.0	106	160	AVD	+	COPD	3.1	65	30.2
13	M	60	101.2	117	188	CAD	+	MI	3.8	30	52.0
14	M	50	95.0	117	180	CAD	+	MI, RF, PE	4.4	45	50.5
15	F	54	54.4	97	160	CAD+MVD	+	HTN, MI, RF, PE	3.1	69	35.9
16	M	59	93.6	114	184	CAD	–	MI	5.3	55	51.1
17	F	63	72.9	124	155	CAD	+	MI, HTN	3.8	28	37.3
18	F	46	68.8	115	160	CAD	–	HTN, RF	3.9	60	34.8
Mean ± SEM		61 ± 3	80 ± 4	115 ± 2	168 ± 3				3.9 ± .1	54 ± 3	42 ± 2

%IBW, Percent over ideal body weight; *CHF,* congestive heart failure; *LVEF,* left ventricular ejection fraction; *TBW,* total body water (calculated from BIA); *M,* male; *CAD,* coronary artery disease; *HTN,* hypertension; *F,* female; *MI,* myocardial infarction; *DM,* diabetes mellitus; *MVD,* mitral valve disease; *AVD,* aortic valve disease; *COPD,* chronic obstructive pulmonary disease; *RF,* renal failure; *PE,* pulmonary edema.

the enhanced release of hormones that augment salt and water retention, the fluid load associated with priming of CPB, and the type of anesthetic agent used.[8, 9]

Expansion of total body water (TBW) and extracellular fluid compartments has been documented by dilutional techniques after CPB, and these compartments are known to remain expanded until the eighth postoperative day.[10, 11] The consequences of this acute fluid retention on a patient's clinical outcome are largely unknown, although a direct relationship between body weight gain and mortality has been described.[12]

Acute changes in body weight have traditionally been used to assess alterations in body hydration. In patients undergoing CPB an initial weight gain of 1 to 7 kg[8] is followed by weight loss associated with spontaneous or pharmacologically stimulated diuresis. However, weight loss also reflects loss of body fat and protein-containing tissue associated with hypocaloric intake and the catabolic response to operation.[13] Thus when tissue loss and fluid gain occur simultaneously changes in body weight may no longer solely reflect changes in body water. This disparity is particularly common in patients with a prolonged and complicated postoperative course.

Although accurate monitoring of body hydration is highly desirable, precise measurements are often limited by practical constraints. Daily weight and fluid intake and output measurements may be imprecise, and other techniques such as isotope-dilutional studies and measurement of central pressures are time consuming, invasive, and often not suitable for routine bedside evaluation. Furthermore, central pressures reflect intravascular volume and not tissue edema.

The human body is composed of approximately 55% to 60% water and therefore offers little resistance to an electric current.[14] The ability to oppose the conduction of an alternating current is called impedance, which is measurable by bioelectric impedance analysis (BIA), a safe, noninvasive, rapid, inexpensive bedside technique that can be used to determine the resistance of the body. The measurement of resistance is inversely related to TBW.[15-17] The purpose of this study was to evaluate the potential use of BIA in adult cardiac surgical patients and to determine whether this approach could be applied to other groups of critically ill patients.

Material and methods

Subjects. Eighteen patients undergoing either elective or urgent heart operations that necessitated CPB were studied over a 7-day period (Table I). The patients received a variety of medications, as determined by their individual physicians. The protocol was approved by the Hospital's Committee for the Protection of Human Subjects from Research Risks, and signed informed consent was obtained from all patients before operation.

Anesthetic and bypass techniques were uniform in all patients. The circuit was primed with isotonic solution (2.1 ± 0.1 L, mean plus or minus standard error of the mean [SEM]) in all cases, and mild hypothermia was used (range 26° to 32° C). BIA measurements were obtained the night before operation, within 2 hours after operation, and then daily. Patients were studied after overnight bed rest and in the fasting state.

During each measurement subjects remained in a semi-recumbent position with the limbs in slight abduction. Body weight (Slingscale 2001-A, Scale-Tronix, Inc., White Plains, N.Y.), fluid balance, and standard clinical chemistry values (hematocrit, white blood cell count, and serum sodium) were also recorded during the hospital stay. The patients were treated with diuretics, vasoactive drugs, and fluid restriction as necessary.

Whole body and regional impedance measurements. Adhesive surface electrodes (RJL Systems, Mt. Clemens, Mich.) were positioned as previously described.[16, 18] The impedance readings were obtained with the use of current-transmitting clips of an impedance plethysmograph (800 μA; model 101A, RLJ Systems, Detroit, Mich.), which were connected to the electrodes. The skin was cleaned with alcohol at the sites of the electrode placement. The limbs were slightly abducted and palms were placed flat on the bed. Measurements for "whole body" and body segments were obtained. Those measurements determined from electrodes placed on proximal portions of the forearm and lower leg are referred to as *proximal.* Electrodes placed on the shoulder and lower leg were used to obtain values referred to as *shoulder.* Measurements were also taken in the trunk, arm, and unoperated leg. The impedance to the conduction of current was displayed by the plethysmograph. The night before each measurement the plethysmograph was charged and calibrated with a standard resistor.

Definitions and calculations. Two components contribute to the measured electrical impedance, Z (ohms). The larger is resistance (R), which accounts for 98% of the signal, whereas only a small contribution (2%) arises from reactance (Xc). Reactance reflects the part of impedance that is caused by the storage of electric charge (capacitance). Impedance is calculated by the following formula:

$$Z = \sqrt{(R^2 + Xc^2)}.$$

TBW was calculated from whole body resistance with the use of group and sex-specific equations described by Kushner and Schoeller[19]:

$$\text{men: TBW} = 0.396\ (\text{height}^2/R) + 0.143\ (\text{weight}) + 8.399$$

$$\text{women: TBW} = 0.382\ (\text{height}^2/R) + 0.105\ (\text{weight}) + 8.315$$

Daily fluid balance was calculated from intake and output data in the patient's medical records, including intravenous and oral fluids, chest tube drainage, urine volume, and estimates of insensible losses.[20]

Changes in the impedance variables and body weight were compared with preoperative data taken at baseline. The daily fluid balance was expressed as cumulative values and compared with changes in resistance and body weight.

Statistical analysis. Data were analyzed with statistical software (STATISTICA 3.0b, StatSoft Inc., Tulsa, Okla.) on a personal computer (Macintosh LC III, Apple Computer, Inc., Cupertino, Calif.). One-way analysis of variance of repeated measures was used to determine whether measurements of impedance and body weight changed during the study period. Pairwise post-hoc comparisons of means were made by Fisher's probability least standard deviation test. Linear regression analysis that accounted for between-subject variability[21] was used to describe relationships between changes in impedance, body weight, and cumulative fluid balance. Multiple regression analysis was done by forward stepwise regression. A probability value less than 0.05 was considered statistically significant. Results are expressed as the mean plus or minus the SEM.

Results

Indications for bypass were coronary artery disease ($n = 16$), mitral valve disease ($n = 2$), and combined coronary artery disease and aortic valve disease ($n = 2$) (Table II). The number of coronary arteries bypassed ranged from two to five.

Preoperative confounding diagnoses included hypertension ($n = 14$), myocardial infarction ($n = 10$), congestive heart failure ($n = 9$), diabetes mellitus ($n = 5$), and renal failure ($n = 2$).

All 18 patients survived and were discharged from the hospital after operation and recovery. The change in hematocrit value reflected the blood loss and hemodilution. Within the group neither serum sodium value nor white blood cell count changed significantly over time (Table III).

Alterations in body weight and whole body resistance detected fluid retention caused by CPB (Fig. 1). Cumulative fluid balance also was associated with changes in resistance (Fig. 2). On the first postoperative day the alterations in whole body resistance were greater in female than in male patients ($p < 0.05$). However, the differences were not reflected in the initial change in body weight. This difference in resistance changes was no longer detected on the following postoperative days.

Changes in body weight and whole body resistance were both correlated with cumulative fluid balance ($r = 0.84$, $p < 0.001$, and $r = -0.81$, $p < 0.001$, respectively) (Table IV). These relationships were similar to each other. Change in body weight was also related to whole body resistance ($r = -0.89$, $p < 0.001$). Correction for patient's height did not significantly improve the relationships between resistance and both fluid balance and weight ($r = 0.83$ and 0.91, respectively).

Regional measurements also detected postoperative fluid gain (Fig. 3). Relatively similar alterations

Table II. *Procedures and postoperative outcome*

Patient	Procedure	Type	No. of vessels	AC (min)	CPB (min)	Temp. (° C)	Op. time (hr:min)	Vent (days)	ICU (days)	Hospital (days)	Complications
1	CABG	E	2	49	77	28	5.50	1	1	13	MI
2	CABG	E	3	58	90	28	5.00	2	7	17	UI
3	CABG	E	3	50	63	30	3.25	2	2	7	WI
4	CABG	E	4	53	91	28	4.00	2	2	5	None
5	CABG	E	4	56	102	28	5.40	1	1	11	WI
6	CABG	E	4	71	105	28	5.24	2	3	8	*R/MI/AF
7	MVR	E	0	156	188	26	5.20	2	3	15	AF
8	CABG+AVR	E	2	126	149	28	5.25	1	2	8	Atel/AF
9	CABG	E	3	47	74	28	4.23	1	1	6	AVT
10	CABG+AVR	E	2	141	160	28	6.00	2	11	25	PE/AF/P.ef/UI
11	CABG	U	4	63	106	28	6.05	2	6	15	Atel/PE
12	AVR	E	0	92	122	28	6.00	12	24	65	†R/AF/Pne
13	CABG	E	3	87	134	32	5.50	1	1	7	None
14	CABG	U	5	113	138	28	6.15	1	2	5	AF
15	CABG+MVR	E	1	103	130	30	6.00	3	6	11	†R
16	CABG	E	3	73	122	28	6.30	1	4	6	None
17	CABG	U	3	83	141	28	5.50	6	8	13	None
18	CABG	E	2	43	54	30	4.00	1	4	13	None
Mean ± SEM			2.7 ± 0.3	81 ± 8	113 ± 8		5.3 ± 0.2	2.3 ± 0.6	4.7 ± 1.3	13 ± 3	

AC, Aortic clamp; *Temp.,* temperature; *Op.,* operation; *Vent,* ventilator; *CABG,* coronary artery bypass grafting; *E,* elective; *MI,* myocardial infarction; *UI,* urinary infection; *WI,* wound infection; **R,* reoperation (myocardial infarction); *AF,* atrial fibrillation; *MVR,* mitral valve replacement; *AVR,* aortic valve replacement; *Atel,* atelectasis; *AVT,* atrioventricular tachycardia; *PE,* pulmonary edema; *P.ef,* pleural effusion; *U,* urgent; *†R,* reoperation (hemorrhage); *Pne,* pneumonia.

Table III. *Mean blood chemistry values during hospitalization*

Day	Hct (%)	WBC (10^{-9}/L)	Na (mEq/L)
Preop.	38.8 ± 1.2	8.14 ± 0.4	138 ± 0.8
1	24.8 ± 1.1*	9.26 ± 0.5	137 ± 1.5
3	26.0 ± 1.1*	10.20 ± 1.0	137 ± 0.9
5	28.9 ± 1.0*	8.68 ± 0.9	136 ± 1.5
7	30.6 ± 2.1*	8.89 ± 1.2	138 ± 1.8

Hct, Hematocrit; *WBC,* white blood cell count; *Na,* Serum sodium.
*$p = 0.01$ versus preoperative values by analysis of variance and Fisher's probability least standard deviation.

were observed in whole body, trunk, proximal, and shoulder segments in contrast to the signal in the leg.

Multiple regression analysis was done to determine those variables significantly influencing the length of intensive care unit (ICU) and hospital stay. These included age, gender, height, percentage over ideal body weight, initial change in weight and whole body resistance, number of vessels bypassed, diagnosis, congestive heart failure, preoperative albumin concentration, left ventricular ejection fraction, aortic clamp time, CPB time, bypass temperature, and operation time.

The initial change in whole body resistance was the primary factor influencing length of hospital stay. Other factors such as prolonged operative periods and low preoperative albumin concentrations also influenced outcome (Table V). Patients whose resistance values returned earlier to preoperative values tended to have fewer postoperative complications (not significant).

Discussion

In this study we performed serial measurements of the body's resistance to an electric current in a group of patients undergoing CPB. Previous studies have validated the ability of BIA to predict TBW.[17] However, only recently have the relationships between changes in the electric resistance of the body and changes in body fluid balance (and/or weight) been measured in critically ill patients. The present study confirms that BIA is a reliable method of monitoring fluid shifts after CPB. Infusion of large fluid volumes can be detected by measuring body resistance,[22] and this method may be used along with body weight and fluid balance to monitor changes in body water. The late return of whole body resistance to baseline values suggested that the patients may have remained overhydrated at the time of hospital discharge, despite the early return of body weight to preoperative values. The calculation of TBW was derived from equations that were determined from normal populations and thus they may not be the most precise method for determ-

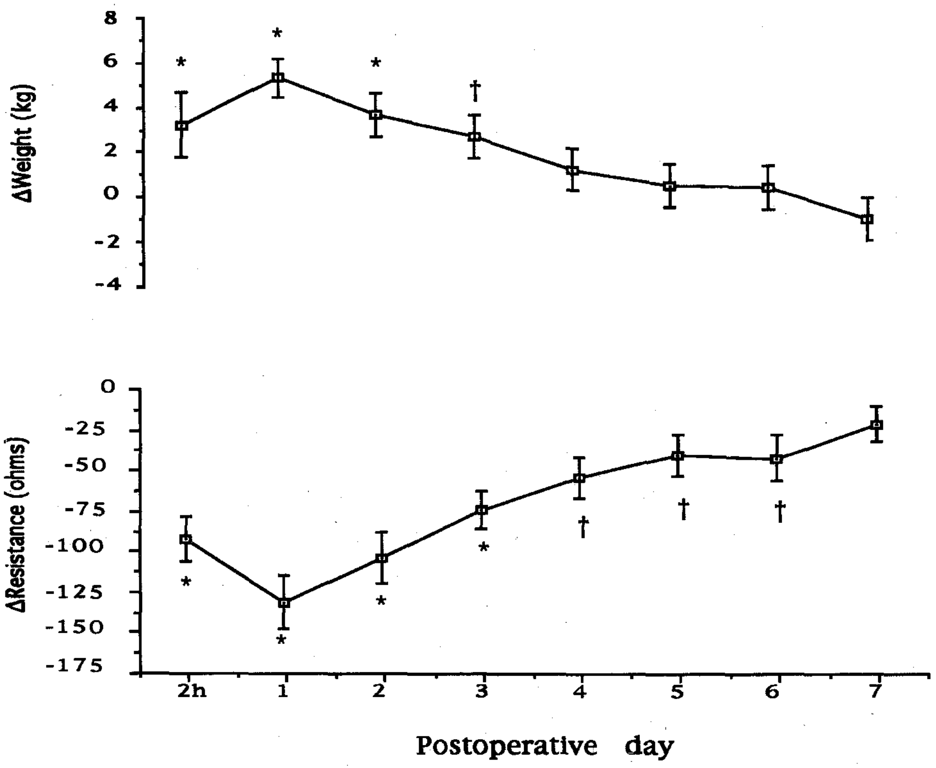

Fig. 1. Changes in body weight and whole body impedance. Fluid accumulation was reflected by initial gain in body weight and decrease in resistance. With postoperative diuresis body weight and resistance returned to preoperative values. However, although body weight returned on day 4, resistance returned on day 7. $^{*}p < 0.001$; $^{\dagger}p < 0.01$ versus baseline by analysis of variance and Fisher's probability least standard deviation.

ing changes in body water in postbypass patients. Body resistance may be more sensitive to water changes than body weight, which may be related to sequestration of fluid in the thorax or abdomen or changes in intracellular or extracellular solute concentration.

The resistance in the leg seemed to be more closely related to changes in weight (see Fig. 3) and this may be a more clinically applicable method of monitoring water content in critically ill patients.

In addition, correcting resistance for height (that is, height^2/whole body resistance) explained 82% of body weight variability and had the lowest estimated standard error compared with single resistance measurements. However, the use of this formula throughout the study did not significantly improve the relationship between weight and whole body resistance, and from a practical standpoint we have favored monitoring percent change in resistance that occurs in the leg. However, one should be aware that resistance in the extremities, particularly in the arms of cardiac surgical patients, may be influenced by gravity, operation, and intravenous infusions.[23] Measurements in the nonoperated leg may be more appropriate because the conduction through this homogeneous cylinder may most accurately represent changes in body hydration.

Others have related postbypass fluid retention and weight to mortality. Analysis of our data in a small group of patients revealed that the greater initial changes in whole body resistance are related to a more prolonged hospital and ICU stay. Other variables associated with this effect included the length of the operation and the initial level of serum albumin. A greater change in resistance was also associated with a longer period of mechanical ventilation.

The results of this study confirm that BIA (50 kHz) is a satisfactory noninvasive method of following water balance in patients undergoing CPB.

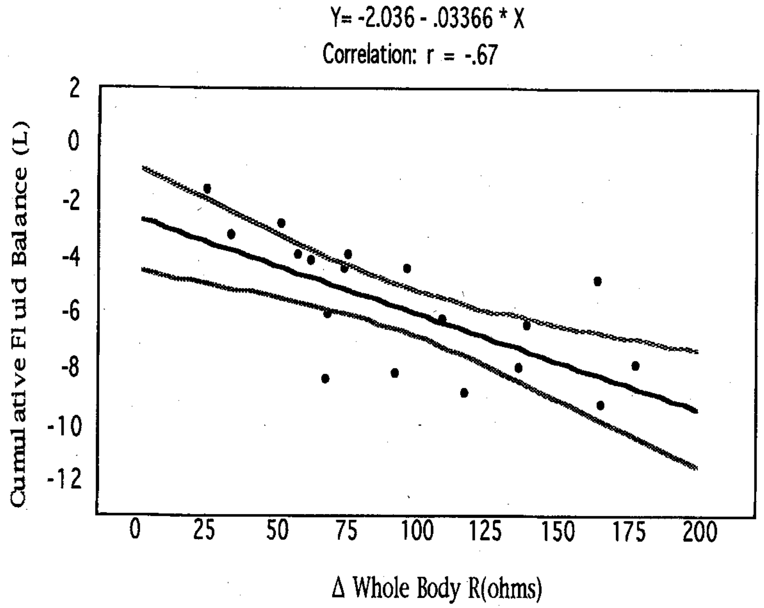

Fig. 2. Relationship between change in whole body resistance *(R)* and cumulative fluid balance in all subjects ($r = -0.67$, $p < 0.01$). *Data points* represent values after postoperative diuresis. Change in resistance detected water fluctuations after CPB and thus can be used to monitor fluid status when dramatic fluid changes occur.

Table IV. *Linear relationships between cumulative fluid balance, change in body weight, and impedance in patients undergoing CPB*

Dependent	*Independent*	*r*	*SEE**	*Intercept*	*Beta (slope)*	*SE of beta coefficient†*
CFB	ΔR whole body	0.81	2.30	−4.52	−0.94	0.08
	ΔR proximal	0.76	2.55	−4.92	−1.08	0.11
	ΔR shoulder	0.72	2.73	−4.63	−0.87	0.10
	ΔR trunk	0.68	2.86	−5.35	−1.10	0.15
	ΔR leg	0.55	3.29	−1.87	−0.60	0.17
	ΔR arm	0.71	2.76	−4.33	−0.94	0.11
	$\Delta Ht^2/R$ whole body	0.83	2.18	−4.45	0.91	0.07
	$\Delta Ht^2/R$ proximal	0.74	2.63	−3.96	0.91	0.10
	ΔTBW	0.79	2.41	−3.58	0.85	0.08
	ΔWt	0.84	2.08	−3.22	1.26	0.09
ΔWt	ΔR whole body	0.89	2.07	−0.08	−0.49	0.06
	ΔR proximal	0.88	2.14	−0.42	−0.58	0.08
	ΔR shoulder	0.90	1.96	−0.79	−0.57	0.06
	ΔR trunk	0.86	2.23	−0.73	−0.60	0.10
	ΔR leg	0.83	2.57	1.61	−0.32	0.11
	ΔR arm	0.87	2.21	−0.09	−0.52	0.08
	$\Delta Ht^2/R$ whole body	0.91	1.94	−0.16	0.51	0.05
	$\Delta Ht^2/R$ proximal	0.89	2.11	0.06	0.53	0.06

Cumulative fluid balance *(CFB)* and changes in body weight *(ΔWt)* were associated with changes in whole body and segmental resistance *(ΔR)* measurements throughout the study period. Relationships between changes in resistance adjusted for patient's height *($\Delta Ht^2/R$)* and change in TBW *(ΔTBW)* were also established. *SEE,* standard error of the estimate; *SE,* standard error.

*$p < 0.001$ for all values.

†$p < 0.001$ for all values except ΔR trunk versus ΔWt were $p < 0.006$.

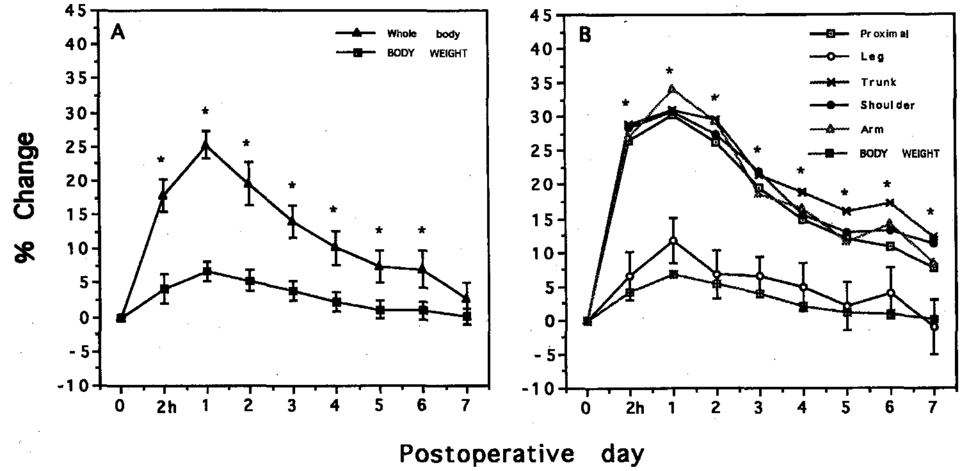

Fig. 3. Comparison of percentage change in whole body and segmental resistance with change in body weight after CPB. **A,** Whole body measurements were significantly different until postoperative day 6. **B,** Other body segments except leg segment were different throughout study. $*p < 0.01$ versus weight by analysis of variance and Fisher's probability least standard deviation. *Error bars* are omitted in some instances for clarity.

Table V. *Multiple regression analysis of outcome variables and whole body resistance*

Dependent	*Multi-R^2*	*Independent*	*Beta*	*SEE*	*p Value*
Hospital stay	$R^2 = 0.69, p = 0.002$	ΔR (day 1)	−0.53	0.17	0.007
	$n = 18$	Operation time	0.36	0.15	0.031
		ΔWt (day 1)	0.36	0.15	0.038
		Preop. albumin	−0.31	0.17	0.096
ICU stay	$R^2 = 0.69, p = 0.002$	ΔR (day 1)	−0.48	0.17	0.015
	$n = 18$	Operation time	0.38	0.15	0.030
		Preop. albumin	−0.48	0.18	0.047
		CPB temperature	−0.19	0.16	0.276
Ventilator duration	$R^2 = 0.50, p = 0.005$	ΔR (day 1)	−0.64	0.18	0.003
	$n = 18$	CHF	0.20	0.32	0.123

Outcome variables were influenced primarily by the initial change in resistance *(ΔR)*. Other factors that significantly influenced such variables were operation time, change in body weight *(ΔWt)*, and preoperative albumin concentration. *CHF,* Congestive heart failure.

Continuous monitoring of fluid changes by BIA can be useful in accurately assessing changes in body hydration in critically ill patients. The relative changes measured over time seem more appropriate than the calculation of absolute volume of TBW on a daily basis. We believe that this technique will be most useful in ICU patients with morbid postoperative convalescence who simultaneously have tissue loss and fluid gain. Under such circumstances body weight may not accurately reflect changes only in body water. Although the role of BIA in predicting outcome is largely unknown, it may be a promising technique for monitoring fluid retention and its distribution in the critically ill.

REFERENCES

1. Cohn LH, Angell WW, Shumway NE. Body fluid shifts after cardiopulmonary bypass. J Thorac Cardiovasc Surg 1971;62:423-9.
2. Downing SW, Edmunds H. Release of vasoactive substances during cardiopulmonary bypass. Ann Thorac Surg 1992;54:1236-43.
3. Videm V, Fosse E, Mollnes TE, Garred P, Svennevig JL. Time for new concepts about measurement of complement activation by cardiopulmonary bypass? Ann Thorac Surg 1992;54:725-31.
4. Jansen NJ, Van Oeveren W, Van Vliet MH, Eijsman L, Wildevuur CR. Endotoxin release and tumor necrosis factor formation during cardiopulmonary bypass. Ann Thorac Surg 1992;54:744-8.

5. Beattie HW, Evans G, Garnett ES, Regoeczi E, Webber CE. Albumin and water fluxes during cardiopulmonary bypass. J THORAC CARDIOVASC SURG 1973;67:926-31.
6. Beattie HW, Evans G, Garnett ES, Webber CE. Sustained hypovolemia and extracellular fluid volume expansion following cardiopulmonary bypass. Surgery 1972;71:891-7.
7. Gilder H, Moody FG, Beal JM. Water distribution in surgical patients. J Surg Res 1962;2:59-65.
8. Utley JR, Stephens DB. Fluid balance during cardiopulmonary bypass: pathophysiology and techniques of cardiopulmonary bypass. Baltimore: Williams and Wilkins, 1982:23-35.
9. Cleland J, Pluth JR, Tauxe WN, Kirklin JW. Blood volume and body fluid compartment changes soon after closed and open intracardiac surgery. J THORAC CARDIOVASC SURG 1966;52:698-705.
10. Moore FD, Olesen KH, McMurrey JD, Parker HV, Ball MR, Boyden CM. The body cell mass and its supporting environment: body composition in health and disease. Philadelphia and London: WB Saunders, 1963.
11. Pacifico AD, Digerness S, Kirklin JW. Acute alterations of body composition after open intracardiac operations. Circulation 1970;61:331-40.
12. Lowell JA, Schifferdecker C, Driscoll DF, Bennotti PN, Bristrian R. Postoperative fluid overload: not a benign problem. Crit Care Med 1990;18:728-33.
13. Johnson DJ, Brooks DC, Wilmore DW, et al. Hypothermic anesthesia attenuates postoperative proteolysis. Ann Surg 1986;204:419-29.
14. Thomasset A. Propriétés bio-électriques des tissus: mesures del'impédance en clinique—signification des courbes obtenues. Lyon Med 1963;208:107-18.
15. Scheltinga MR, Jacobs DO, Kimbrough TD, Wilmore DW. Identifying body fluid distribution by measuring electrical impedance. J Trauma 1992;33:665-70.
16. Scheltinga MR, Jacobs DO, Kimbrough T, Wilmore DW. Alterations in body fluid content can be detected by bioelectrical impedance analysis. J Surg Res 1991; 50:461-8.
17. Kushner RF, Schoeller DA, Fjeld CR, Danford L. Is the impedance index (Ht^2/R) significant in predicting total body water? Am J Clin Nutr 1992;56:835-9.
18. Lukaski HC, Bolonchuk WW, Hall CB, Siders WA. Validation of tetrapolar bioelectrical impedance method to assess human body composition. J Appl Physiol 1986;60:1327-32.
19. Kushner RF, Shoeller DA. Estimation of total body water by bioelectrical impedance analysis. Am J Clin Nutr 1986;44:417-24.
20. Cox P. Insensible water loss and its assessment in adult patients: a review. Acta Anaesthesiol Scand 1987;31:771-6.
21. Gleant SA, Flinker BK. Accounting for between subjects variability: primer of applied regression and analysis of variance. New York: McGraw Hill, 1990:381-90.
22. Scheltinga MR, Helton WS, Rounds J, Jacobs DO, Wilmore DW. Impedance electrodes positioned on proximal positions of limbs quantify fluid compartments in dogs. J Appl Physiol 1991;70:2039-44.
23. Zillikens MC, VandenBerg J, Wilson JHP, Swart GR. Whole body and segmental bioelectrical-impedance analysis in patients with cirrhosis of the liver: changes after treatment of ascites. Am J Clin Nutr 1992;55:621-5.